MODIS On-orbit Characterization Using the Moon

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ABSTRACT

The MODIS Protoflight Model (PFM) on-board the Terra spacecraft has been in operation for more than two and half years since its launch on December 18, 1999. In addition to the on-board calibrators (OBCs), the observations of the moon have been planned monthly with carefully chosen viewing conditions. The data from these observations is used to support the instrument s on-orbit calibration and characterization. In this paper, we describe the use of lunar observations for monitoring the MODIS reflective solar bands (RSB) radiometric stability and discuss related applications. For Terra MODIS, the lunar views have also been used to derive correction parameters for the optical leak among the photoconductive (PC) detectors (bands 31-36), to characterize the electronic crosstalk under different focal plane operational configurations, and to track on-orbit band-to-band registration (BBR). The same strategies are being applied to the Aqua MODIS (Flight Model 1 - FM1) launched on May 4, 2002. The lunar observation results from both instruments are compared.

Keywords: MODIS, Moon, calibration, optical leak, electronic crosstalk, radiometric stability

1. INTRODUCTION

The MODerate Resolution Imaging Spectroradiometer (MODIS) is the keystone instrument for the NASA Earth Observing System (EOS)[1]. Both EOS Terra and Aqua satellites carry a MODIS instrument with Terra in a 10:30AM (local time) equator crossing orbit and Aqua in a 1:30 PM orbit. The Protoflight Model (PFM) on-board the Terra spacecraft has been in operation for more than two and half years since its launch on December 18, 1999. The Flight Model (FM1) was launched on May 4, 2002 on-board the Aqua spacecraft. The two instruments provide complementing morning and afternoon global observations for the studies of the Earth/Atmosphere system.

The MODIS instrument provides measurements in 36 spectral bands with wavelengths from 0.412μ (VIS) to 14.5μ (LWIR) at three nadir spatial resolutions: 2 bands at 250m, 5 bands at 500m, and 29 bands at 1km. It is a cross-track scanning radiometer with a two-sided paddle wheel scan mirror, providing a swath of 10km (nadir) along-track by 2330km cross-track every scan (1.478 sec.). Figure 1 is a schematic of the MODIS scanning sequence. The rotating scan mirror allows the sensor to view the on-board calibrators (OBCs) and the Earth scene every scan. The OBCs include a solar diffuser panel used for calibration of the reflective solar bands (RSB), bands 1-19, and 26 with wavelengths from 0.412μ to 2.1μ, and a v-grooved blackbody for calibration of the thermal emissive bands (TEB), bands 20-25 and 27-36 with wavelengths from 3.75μ to 14.5μ[2-5]. Any degradation of the SD is monitored using a solar diffuser stability monitor (SDSM) during each SD calibration via alternate views of the direct Sun light and the reflected Sun light from the SD. Another on-board device, the spectroradiometric calibration assembly (SRCA), is used to monitor the sensor s on-orbit spatial and spectral characterization[6].

Since the Moon provides a good radiometric reference for the Earth-orbiting sensors with its stable surface reflectance and irradiance[7-10], it has been used by the MODIS to monitor detector response stability in the visible (VIS) and near-infrared (NIR) spectral regions. In this paper, we will briefly review the method used for the response stability monitoring and provide the results for the Terra MODIS since it has been in operation for over two and half years. In addition, the Moon has been used for other on-orbit calibration and characterization activities. These include deriving correction parameters for the Terra MODIS optical leak among the photoconductive (PC) detectors (bands 31-36), characterizing the electronic crosstalk under different focal plane operational configurations, and tracking changes in the band-to-band registration (BBR). We will present the results of these applications to both Terra MODIS and Aqua MODIS and provide performance comparisons between the two instruments using their lunar observations.

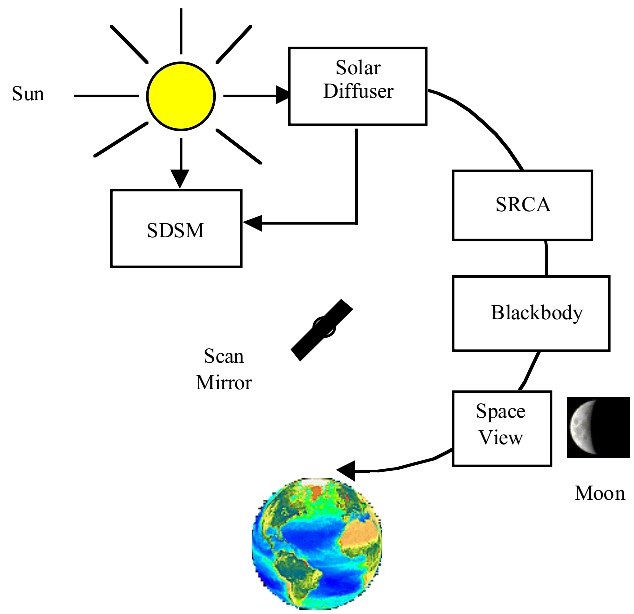

Figure 1: MODIS scanning sequence for on-orbit calibration and characterization.

2. MONITORING MODIS RSB RADIOMETRIC STABILITY USING THE MOON

The key application of using the Moon for MODIS on-orbit calibration and characterization is to monitor the RSB radiometric stability in the VIS and NIR spectral regions. Monthly lunar observations have been planned and implemented throughout the MODIS on-orbit operations. The sensor views the Moon through its space view port via a spacecraft roll maneuver. The lunar observations are scheduled for optimal viewing conditions so as to minimize the corrections needed for lunar phase and libration. The results obtained from the lunar observations are used together with those from the SD. In the following, we will begin with a brief description of the MODIS RSB calibration approach for using the solar diffuser (SD) and solar diffuser stability monitor (SDSM) system. Then we will discuss the methodology developed for monitoring the sensor s response stability using the lunar observations and the application of any response change to the MODIS calibration.

The MODIS calibration is band, detector, sub-frame (for 250m and 500m resolution bands), mirror side, and scan angle dependent. The MODIS Level 1B algorithms (code) convert instrument response in digital number to radiometrically calibrated and geolocated top of atmosphere (TOA) radiance or reflectance. The primary product of the reflective solar bands is the Earth scene reflectance factor, $\rho_{EV}\cos(\theta_{EV})$, given by[5],

$$\rho_{EV}\cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{Earth\_Sun}, \tag{1}$$

where m_1 is the reflectance scaling coefficient derived from the SD (with known BRF) calibration,

$$m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{dn^*_{SD} \cdot d^2_{Earth\_Sun}} \cdot \Delta_{SD} \cdot \Gamma, \tag{2}$$

dn^*_{EV} is sensor's earth view response in digital number with instrument background subtracted and other effects corrected and dn^*_{SD} is the corresponding response from the SD view. Since the SD and EV views are not carried out at the same time or at the same geo-location, an Earth-Sun distance correction factor, d_{Earth_Sun} (normalized to 1AU) must be considered in both Equations. In Eqn. 2, Δ_{SD} is the SD degradation factor determined by the solar diffuser stability monitor (SDSM), and Γ is the SD screen vignetting function[5,11]. Terra MODIS performs regular SD calibration: once per week during the first two years of on-orbit operation and once every other week thereafter. Figure 2 shows the Terra MODIS m_1 trending results for several RSB bands (B3, 8, 9, 10, and 17) over its 2.5 years on-orbit operation. The discontinuities in the trending curves correspond to the instrument electronic configuration changes on October 30, 2002 (day 2000305, from initial A-side to B-side electronics) and on July 2, 2001 (day 2000549, from B-side to A-side electronics).

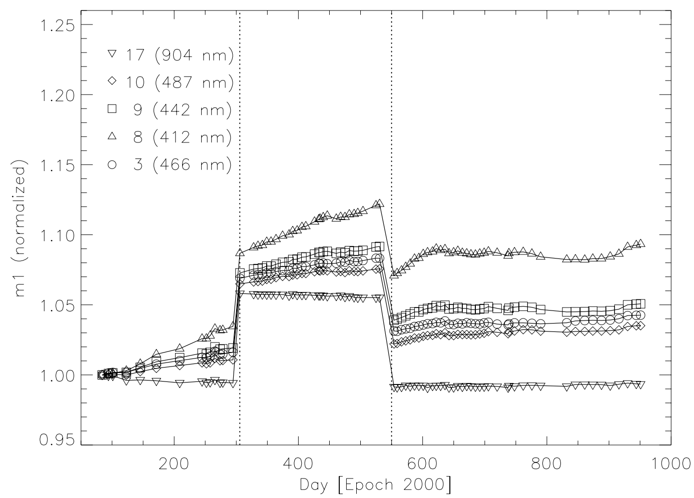

Figure 2: MODIS RSB (bands 3, 8, 9, 10, 17) on-orbit response trending from SD calibration (mirror side 1)

Since m_1 is inversely proportional to the sensor s response (dn), the bands that show larger increasing trend are the ones that have more degradation. This degradation is calibrated out with the time-dependent calibration coefficients. When the Moon is used as a radiometric reference by the MODIS to monitor system response stability in the visible (VIS) and near-infrared (NIR) spectral regions, an equivalent expression to Eqn. 2 can be written as

$$m_1 = \frac{f(view\_geometry)}{dn_{Moon}}. \tag{3}$$

The view geometry factor in Eqn. 3 will correct for the effects of lunar phase angle, liberation angle, the distances between the Sun, the Moon, and the MODIS. It also considers the over-sampling effect in the lunar observations[10]. To minimize the phase angle correction in the response stability trending, the lunar observations by the MODIS sensor are scheduled to keep nearly the same phase angle of 55.5°. Since we are only interested in the relative change of response, a total integrated lunar response is computed. This approach does not need to know the exact lunar irradiance as long as it is stable. After correcting the viewing geometry factor in each observation, the m_1 lunar trending results for bands 3, 8, 9, 10, and 17 are shown in Figure 3.

This trending provides additional information to support the RSB calibration since the lunar observations are performed through the MODIS space view port at an angle of incidence (AOI) of 11.2° to the scan mirror while the SD calibration is at an AOI of 50.2°. Figure 4 illustrates the scan angles of the OBC viewing sectors. The angle of incidence (AOI) on the scan mirror is related to the scan angle, as measured from nadir, by,

$$AOI = \frac{Scan\_Angle}{2} + 38^\circ . \quad (4)$$

The overall trend from the Moon (Figure 3) is similar to that from the SD. The difference in the magnitude of the trending is a direct measure of the mirror degradation rate difference at different AOI to the scan mirror. Both sides of the scan mirror are used in collecting data. The results in Figures 2 and 3 are from mirror side 1 response. Similar results have been obtained for the mirror side 2 response. The information derived from the lunar observation is extremely important. It shows clearly that if the calibration only uses the coefficients derived from the SD, then the scan angle dependent changes of the detector response will not be captured in the Earth scene retrieval when the AOI to the scan mirror is not the same as that of the SD.

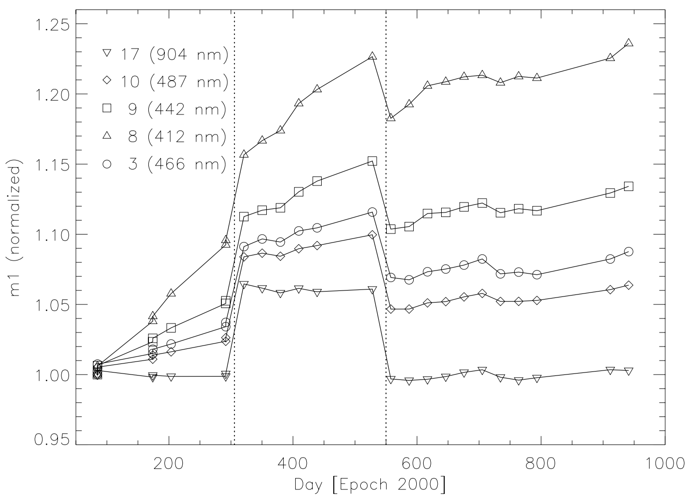

Figure 3: MODIS RSB (bands 3, 8, 9, 10, 17) on-orbit response trending from lunar observations (mirror side 1)

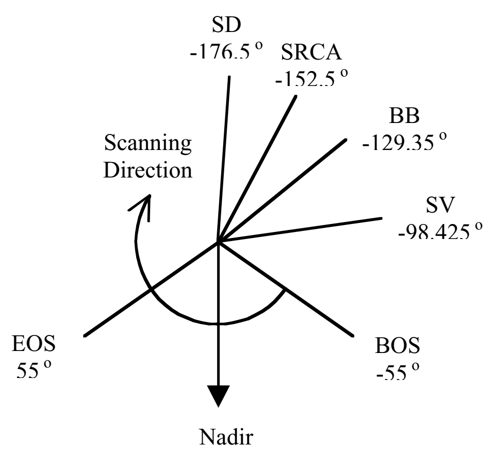

Figure 4: MODIS scan mirror s scan angle with respect to instrument nadir

Using the results from the SD, the Moon, and the SRCA (providing response trending at an AOI of 38.2°), we have developed a time dependent response versus scan angle (RVS) look-up table (LUT) for the Terra MODIS on-orbit calibration. This will reduce the uncertainty at different AOI. The primary calibration of RSBs is still done by the SD observations. The use of Moon and SRCA provide additional information on the response trending at different AOIs. The same approach may also be applied to Aqua MODIS.

3. CORRECTION OF TERRA MODIS PC OPTICAL LEAK

From the Terra MODIS (PFM) pre-launch calibration and characterization, it was found that there was an optical leak from band 31 to the other PC bands on the same LWIR focal plane. Because of this, the responses (dn) of these PC bands (bands 32-36) are contaminated by the light from band 31. This optical leak is corrected in the calibration algorithms by subtracting the contribution from band 31 to the other PC bands. Using band 32 as an example, the relationship between the corrected response (dn^{corr}) and the contaminated response (dn^{cont}) is given by,

$$dn_{B32}^{corr}(F) = dn_{B32}^{cont}(F) - xtalk_{B31->B32} \cdot dn_{B31}(F + FO_{B31-B32}) \tag{5}$$

where the $xtalk_{B31->B32}$ is the crosstalk coefficient from B31 to B32. The actual correction is done pixel by pixel. The F and FO stand for the frame number and frame offset. The frame offset is related to the band 31 and band 32 location on the focal plane. The same expression applies to all other PC bands. The PC bands are thermal emissive bands that use the OBC BB for on-orbit calibration, the above correction must be used on both the BB and Earth scene retrievals.

Figures 5(a)-7(a) are the response profiles (x = frame or pixel, y = scan, z = dn) for Terra MODIS B31, B33, and B35 from actual lunar observations. B31 has no leak. The leaks in B33 and B35 are obvious. Again, the leaking signal location relative to the in band s direct lunar view response is determined by the band location on the focal plane. For example B33 and B31 are 12 frames apart while B31 and B35 are only 6 frames apart.

The lunar observations from the Terra MODIS have been used for updating the crosstalk correction coefficients. Early on-orbit corrections using pre-launch determined coefficients were not completely satisfactory. The on-orbit coefficients (derived from the Moon and Earth scenes) have made substantial improvements. Based on the Terra MODIS PC pre-launch crosstalk characterization, blocking paints were added to the end of the FM1 filters to prevent light from leaking to the other PC bands. For performance comparison purposes, the lunar observations for Aqua MODIS B31, B33, and B35 are shown in Figures 5(b)-7(b). The improvement made in Aqua MODIS (FM1) to remove the PC optical leak is substantial.

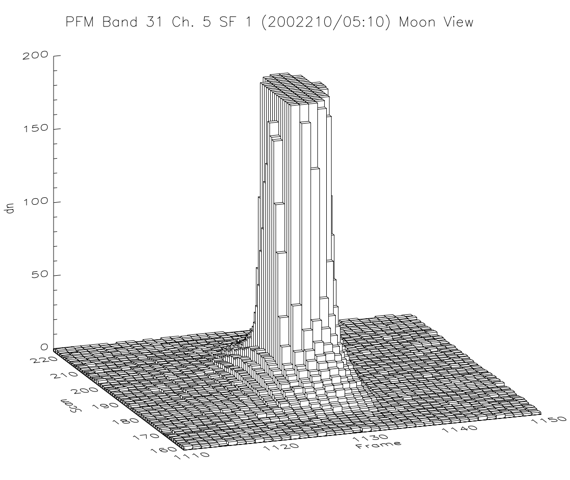

Figure 5(a): Terra MODIS (PFM) B31 lunar response (no optical leak)

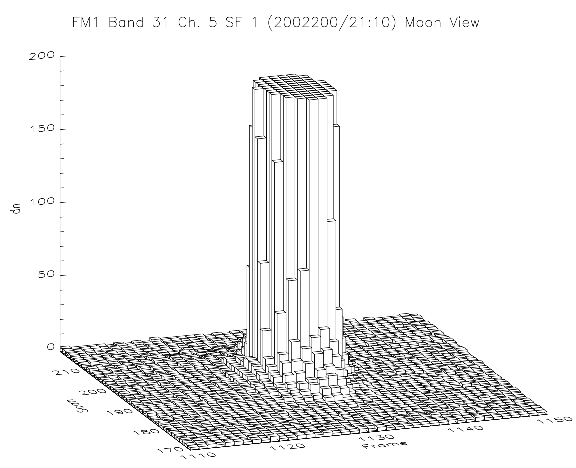

Figure 5(b): Aqua MODIS (FM1) B31 lunar response (no optical leak)

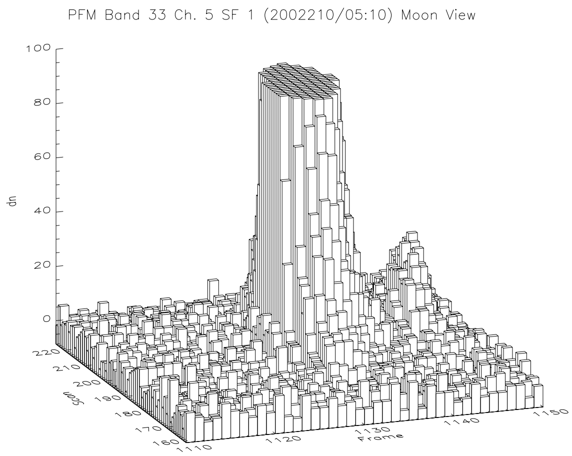

Figure 6(a): Terra MODIS (PFM) B33 lunar response
(with optical leak)

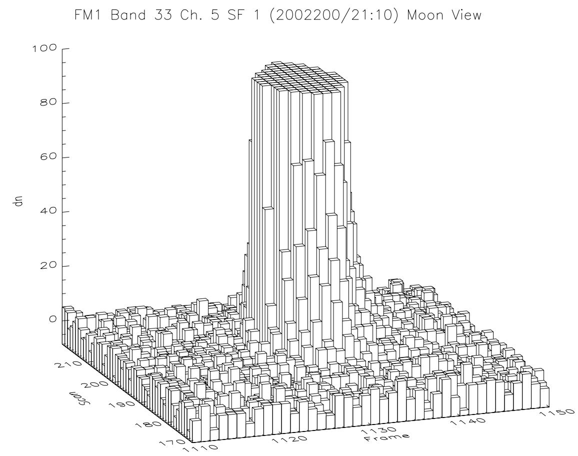

Figure 6(b): Aqua MODIS (FM1) B33 lunar response
(no optical leak)

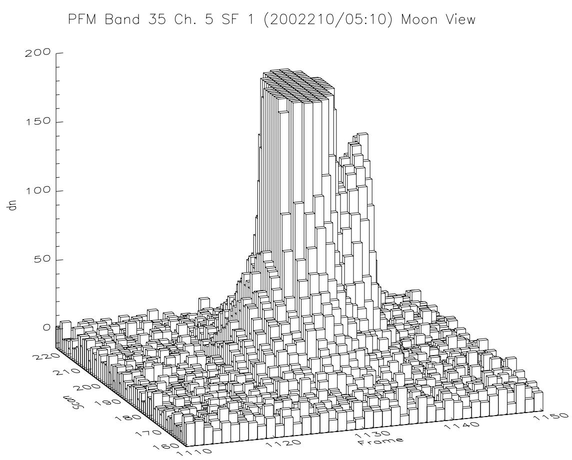

Figure 7(a): Terra MODIS (PFM) B35 lunar response
(with optical leak)

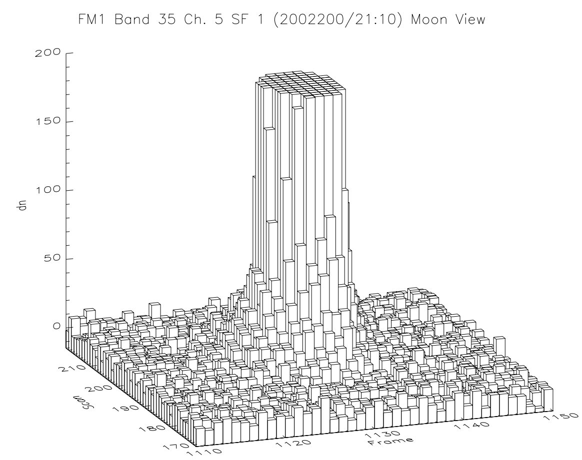

Figure 7(b): Aqua MODIS (FM1) B35 lunar response
(no optical leak)

4. OTHER INSTRUMENT CHARATERIZATION USING THE MOON

In addition to the radiometric stability monitoring for the MODIS reflective solar bands (RSB) and deriving the crosstalk coefficients for the Terra MODIS PC bands optical leak correction, the lunar observations have been used for other instrument on-orbit characterizations. These applications include finding the optimal focal plane operational configuration and tracking the band-to-band registration (BBR) changes on-orbit. In this section we will focus on the lunar observation results at different focal plane bias voltages for Terra MODIS. These results were used at the beginning of the mission for selecting the sensor s on-orbit operational configuration.

Typically, the focal plane operational parameters are determined before final testing on the ground. MODIS 36 bands are distributed on four plane assemblies (VIS, NIR, SMIR, and LWIR). During pre-launch thermal vacuum calibration and characterization, substantial electronic crosstalk was identified between bands/detectors on the SMIR focal plane (bands 5-7, and 20-26). To reduce this crosstalk, some of the resistors controlling the detectors sampling and resetting were replaced. Unfortunately, this change was made after all the radiometric calibration had been performed and there was no validation testing prior to instrument launch.

The MODIS FPA bias voltages can be adjusted on-orbit. During early on-orbit operation, a number of different configurations were used to determine the optimal setting. At each configuration or setting, called Itwk/Vdet (a set of parameters that control the FPA operation), the SMIR band responses to the BB, the SD, and the Moon were carefully analyzed. The factors examined included the detectors operability, amount of electronic crosstalk, and the sub-frame (or sub-sample) difference for the 500m resolution bands (B5-7) which have 2 samples for a corresponding 1km band sample. We present in Figures 8 and 9 the lunar observation results for B5 (sub-frame 1) and B20 that show the electronic crosstalk difference from using two different testing conditions. An Itwk/Vdet configuration of 110/226 was used at the beginning of the Terra mission to remove the sub-frame differences from B5-7 while ignoring the amount of electronic crosstalk on the remainder of the SMIR FPA. Clearly the amount of electronic crosstalk in the current 79/190 (Itwk/Vdet) configuration is much smaller.

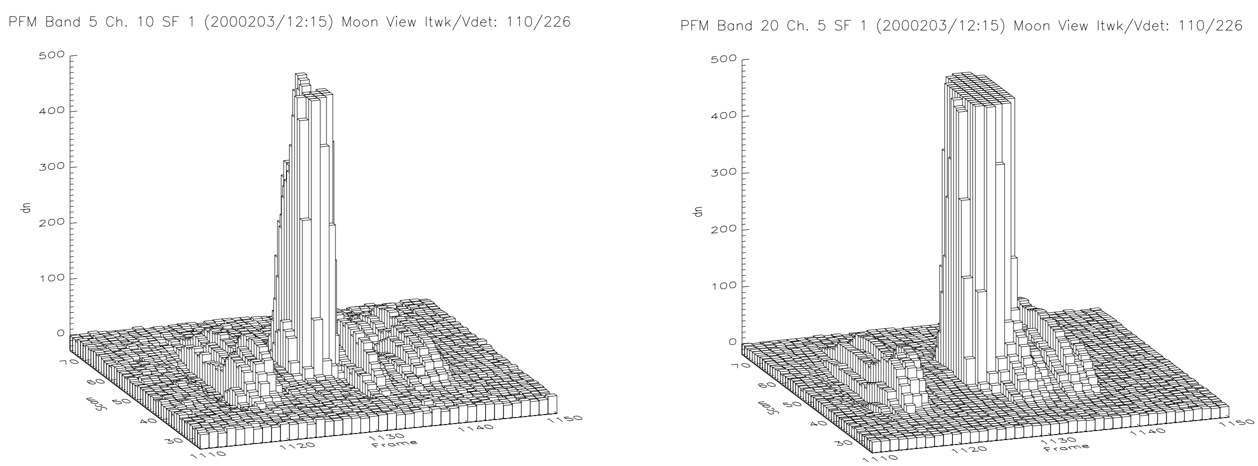

Figure 8: Terra MODIS (PFM) B5 detector 10 (sub-frame 1) and B20 detector 5 lunar response using Itwk/Vdet=110/226

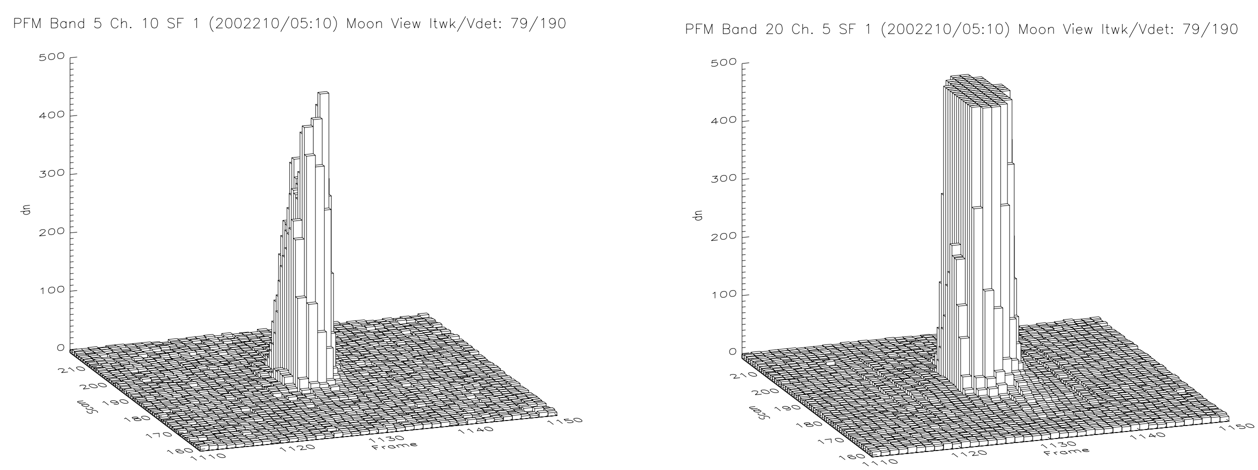

Figure 9: Terra MODIS (PFM) B5 detector 10 (sub-frame 1) and B20 detector 5 lunar response using Itwk/Vdet=79/190

Aqua MODIS (FM1) underwent extensive pre-launch characterization of the SMIR FPA. The operational SMIR Itwk/Vdet = 102/184. No additional on-orbit testing is needed. For comparison purposes, the lunar observation results for B5 (sub-frame 1) and B20 from Aqua MODIS are presented in Figure 10. This is the only configuration used for its on-orbit operation.

MODIS has an on-board device, the spectroradiometric calibration assembly (SRCA), to track the instrument spatial characterization. We have developed an algorithm that uses the lunar data to track the band-to-band registration (BBR) of MODIS. In the VIS/NIR region, the nighttime lunar image has a sharp contrast. The sharp edge of the lunar image as seen by different bands can be used for tracking the spatial characterization of the instrument. The results derived from the MODIS SRCA have been used to validate our Moon approach. Very good agreement between the results from both approaches has been demonstrated in the along scan direction. With small modification, the same approach can be applied to the along track direction. A detailed description of this algorithm and its application to tracking the BBR have been reported by Xiong et. al.[10].

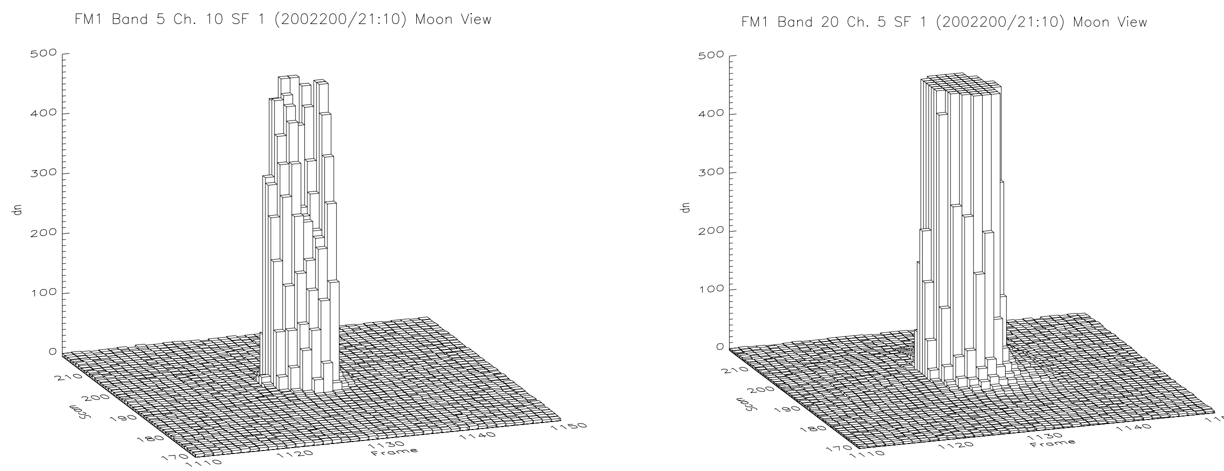

Figure 10: Aqua MODIS (FM1) B5 detector 10 (sub-frame 1) and B20 detector 5 lunar response using Itwk/Vdet=102/184

5. SUMMARY

The Moon has been used extensively by the MODIS to support its on-orbit calibration and characterization. Using the Moon s stable surface reflectance (or irradiance) property, the MODIS radiometric stability is monitored in the VIS and NIR regions using monthly lunar observations with carefully chosen viewing conditions. The results, coupled with those from the regular SD calibration and response trending of the SRCA at different AOIs, have provided important calibration parameters including the time-dependent response versus scan angle (RVS), for the instrument s on-orbit calibration. The Moon s sharp images as seen by different bands (in the VIS/NIR regions) can be used for tracking the band-to-band registration (BBR). These methods can be applied to other Earth-orbiting sensors with minor modifications. Using the lunar observations, we have been able to determine the extent of optical leaks in the PC bands. This has allowed us to make substantial improvements in our on-orbit leak correction. In this paper, we have also shown the application of using the Moon for comparing the sensor s performance at different operational configurations. It has proven to be an effective way of assessing the detector to detector crosstalk. All these applications have played important roles in Terra MODIS on-orbit calibration and characterization. Same approaches have been or will be used with the Aqua MODIS.

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